

Lateral Impacts to PC Girders in Bridges with Intermediate Diaphragms

Robert Abendroth and Fouad Fanous

Department of Civil, Construction and Environmental Engineering

Iowa State University

Ames, IA 50011-3232

rabendro@iastate.edu, fanous@iastate.edu

ABSTRACT

Bridge engineers are concerned about the response of PC girder bridges which are hit by over-height-vehicle loads. The roll of intermediate diaphragms in providing impact-damage protection to the PC girders is not clearly defined. An analytical study was conducted to assess the role of intermediate diaphragms in reducing the damage to the girders of a PC girder bridge that is struck by an over-height object on a highway vehicle. Also, the study investigated whether a structural steel, intermediate diaphragm would essentially provide the same degree of impact protection to the PC girders as that provided by a reinforced concrete, intermediate diaphragm. Finite-element models were developed for non-skewed and skewed, PC girder bridges. Each model was analyzed with one reinforced concrete and two types of steel intermediate diaphragms that were located at mid-span of an interior span of the bridge. The bridge models were analyzed for a lateral-impact load that was applied to the bottom flange of the exterior girders at the diaphragm location and away from the diaphragm location. The induced strains and displacements in the girders were established for each diaphragm case. When a lateral-impact load was applied at the diaphragm location, the reinforced concrete, intermediate diaphragm provided more protection for the girders than that provided by the two types of structural steel, intermediate diaphragms. The three types of intermediate diaphragms provided essentially the same degree of impact protection for the PC girders when the load was applied away from the diaphragm location.

Key words: bridge diaphragms—finite element analysis—lateral impact

INTRODUCTION

Bridge engineers are concerned about the damage that impacts from over-height-vehicle loads cause to prestressed concrete (PC) girder bridges. Shanafelt and Horn (1) noted that about 120 PC girder bridges in the United States are damaged each year by over-height-vehicle loads. The actual number of impacts to bridges is probably significantly higher than these numbers, since many minor collisions are not reported to authorities.

Engineers with the Bridges and Structures Design Section of the Iowa Department of Transportation (Iowa DOT) have historically believed that the mass of a reinforced concrete (RC), intermediate diaphragm will provide a better degree of damage protection to the PC girders than that provided by a steel intermediate diaphragm. However, to reduce the construction time and to simplify the construction process, bridge contractors in the State of Iowa have always expressed a desire to install steel, intermediate diaphragms rather than to construct RC, intermediate diaphragms for PC girder bridges.

This paper discusses whether a steel, intermediate diaphragm with relatively simple connections to the PC girders can provide the same degree-of-damage protection to the PC girders as that provided by the RC, intermediate diaphragm currently being used by the Iowa DOT for both non-skewed and skewed bridges. Detailed finite-element models of several bridges were analyzed with the ANSYS software (2). Even though this investigation did not involve experimental work, the finite-element models were calibrated using the experimental test results that were obtained from published literature.

FINITE ELEMENT CALIBRATIONS

Description of an Experimental Bridge Model

The single-span bridge that was constructed and tested by Abendroth et al. (3) at Iowa State University was used to guide the development of the finite-element models for prototype bridges. The experimental bridge had three, Iowa DOT Type-A38, PC girders that were spaced at 6 ft – 0 in. (1830 mm) on center. The girders supported a 4-in. (100-mm) thick RC deck that was 40 ft – 4 in. (12300-mm) long and 18-ft (5490-mm) wide. At each end of the bridge model, a 42-in. (1070-mm) deep by 18-in. (460-mm) wide, RC abutment supported the PC girders. The ends of the girders were embedded 8 in. (200 mm) into a full-depth, 14-in. (360-mm) thick, RC, end diaphragm. Different types of intermediate diaphragms and locations within the span were considered in those tests.

Finite-Element Model of the Experimental Bridge

The deck and the PC girders of the experimental bridge were modeled using solid elements. Shell elements were used to model the end-diaphragms and the abutments. The different types of intermediate diaphragms were modeled using different types of finite elements. For each diaphragm type, interface elements, which can model sliding and separation between the diaphragm elements and the adjacent elements for the PC girder and RC deck, were used in the analytical models. These models were analyzed for transverse, horizontal loads that were applied to the bottom flange and at the mid-span of either of the exterior girders. Andrawes (4) presented the complete details of the finite-element-modeling techniques for the experimental bridge.

About a 20% difference occurred between the experimentally-measured and analytically-predicted, horizontal displacements for the experimental bridge. The calculated, longitudinal strains in the PC girder were compared to the measured strains. The predicted, longitudinal strains in the PC girders and in the intermediate diaphragms were within about 20% of the measured longitudinal strains. This difference in the predicted and measured strains was attributed to the presences of concrete cracks that existed in the experimental bridge. These cracks were not modeled in the finite-element models. The relative closeness of the analytical predictions to the measured bridge responses revealed that the analytical-modeling techniques were applicable to analyze PC girder bridges that are subjected to lateral forces.

BRIDGES SELECTED FOR THE ANALYSIS

Non-skewed Bridge

The prototype, non-skewed bridge that was selected for this study has four spans, three frame-type piers, and two integral abutments. The length of each end span is 35 ft – 9 in. (10900 mm), while the length for each inner span is 96 ft – 6 in. (29400 mm). An 8-in. (200-mm) thick, bridge deck is supported by five, equally-spaced, Iowa Type-D, PC girders. A 3-ft (910-mm) thick, RC end diaphragm (abutment backwall) was cast at each abutment. At the ends of the PC girders and at the location of the RC intermediate diaphragm, two, $\frac{3}{4}$ -in. (20-mm), diameter, coil rods passed through the bottom flange of each girder and extended into the end diaphragms and intermediate diaphragms. Bent-reinforcing bars connected the bridge deck to the end diaphragm.

Skewed Bridge

A skewed, PC girder bridge was analytically investigated to determine the effect of a skew angle on the response of the bridge to lateral impacts. The skewed bridge that was selected for this study has a 20.4° skew angle, four spans, three frame-type piers, two integral abutments, and five PC girders. Each end span is 45 ft – 9 in. (13900-mm), long and each inner span is 96 ft – 6 in. (29400-mm) long. The bridge girders and deck have similar geometric and material properties and have the same connections between the diaphragms and the PC girders and RC deck as that for the non-skewed bridge.

INTERMEDIATE DIAPHRAGMS

Two steel and one, RC intermediate diaphragm were considered in this study. The steel diaphragms were an X-braced diaphragm with a horizontal strut and a K-braced diaphragm with a horizontal strut. All three types of intermediate diaphragms are standard diaphragms that are used by the Iowa DOT. Andrawes (4) provided additional descriptive information about these intermediate diaphragms.

FINITE ELEMENT MODELING

For all of the finite-element models, the PC girders and the 8-in. (200-mm) thick, RC slab were modeled using solid elements. An isometric view of a single-span, finite-element model is shown in Fig. 1. The 10-in. (250-mm) thick, RC intermediate diaphragms, shown in Fig. 2, were modeled by solid elements. A three-dimensional, truss element was selected to idealize the coil rods that connected the RC intermediate diaphragm to the PC girders. For the two, steel,

intermediate diaphragms that are shown in Figs. 3 and 4, shell elements were used to model the horizontal struts, bent plates, and flat plates. Beam elements were used to model the X-braced and K-braced members.

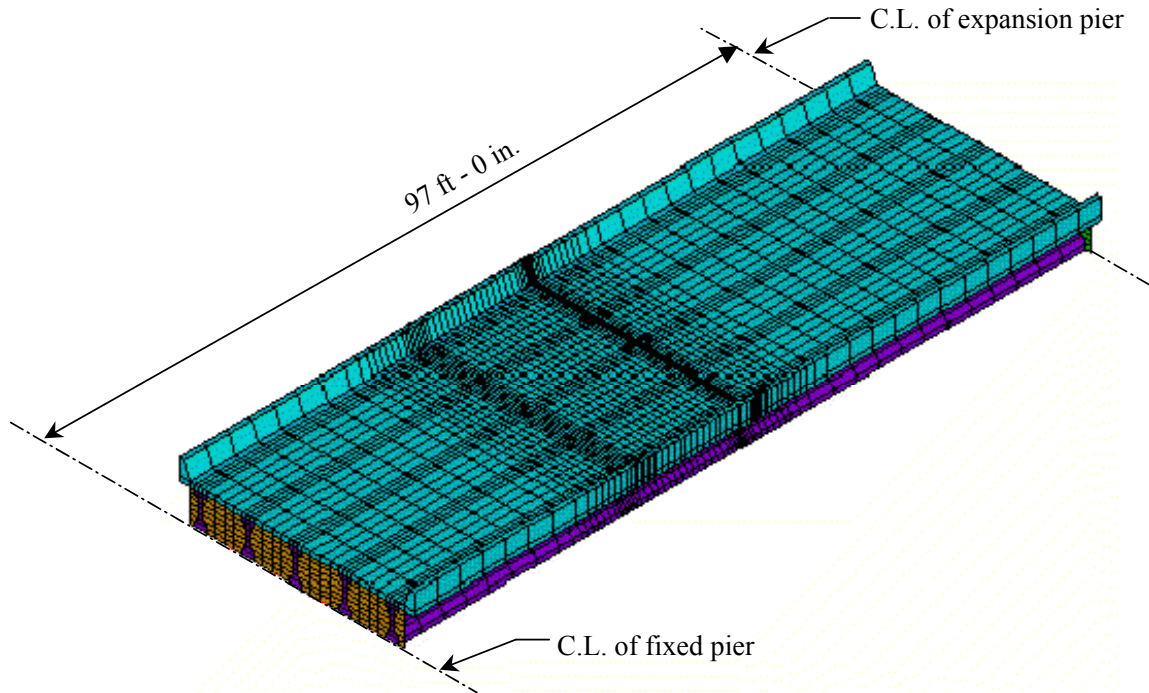
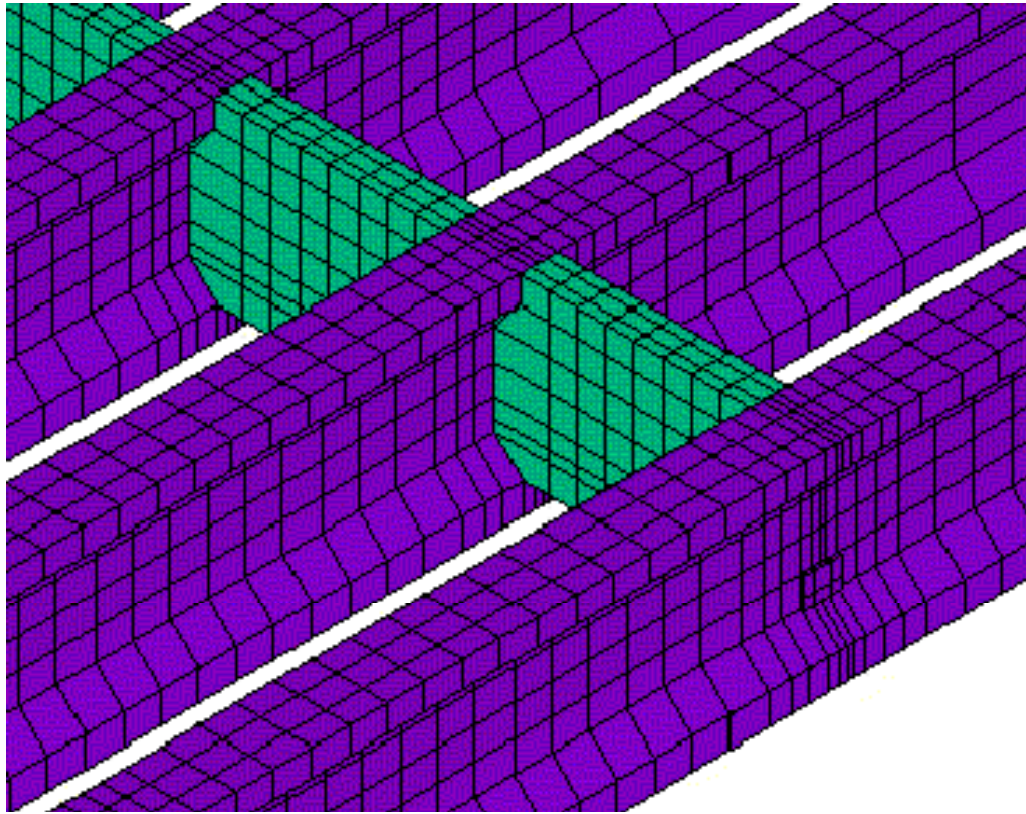


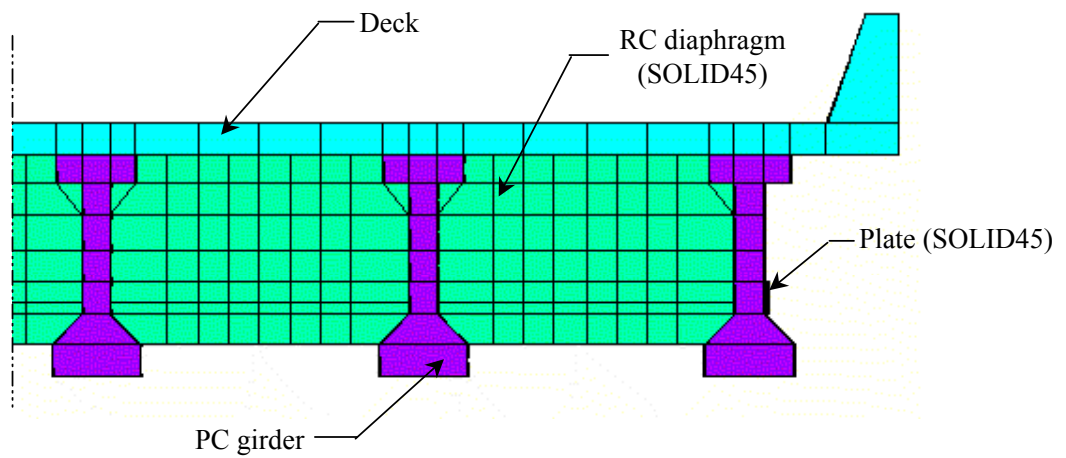
FIGURE 1. Finite-Element Model of the Interior Span of a Non-Skewed Bridge (1 ft. = 305mm)

Finite-element modeling of the connection between the members in the steel intermediate diaphragms and the bent plates that were used to attach the diaphragms to the webs of the PC girders included the use of rigid-link elements; contact elements; and pairs of counteracting, compressive forces. The length of the rigid-link elements accounted for the eccentricity between the center of gravity for the diaphragm members and the outstanding leg of the bent plate. Contact elements with a coefficient of friction equal to 0.33 were placed between the interface surfaces of the connection to permit slippage between the parts. The counteracting, compressive forces represented the clamping force that is developed in a connection when high-strength bolts are installed in a fully-tensioned condition.

The bolts that connected the steel diaphragms to the PC girders were modeled as three-dimensional, truss elements. Since the high-strength bolts for the steel diaphragms and the coil rods for the RC diaphragms provided the connections between the diaphragms and the girders, common nodes were not used between the elements for the diaphragms and the elements for the bridge deck or girders. Contact elements were utilized on all interface surfaces where slippage and separation might occur along those surfaces. The concrete and steel, material strengths were assumed to be linearly elastic.

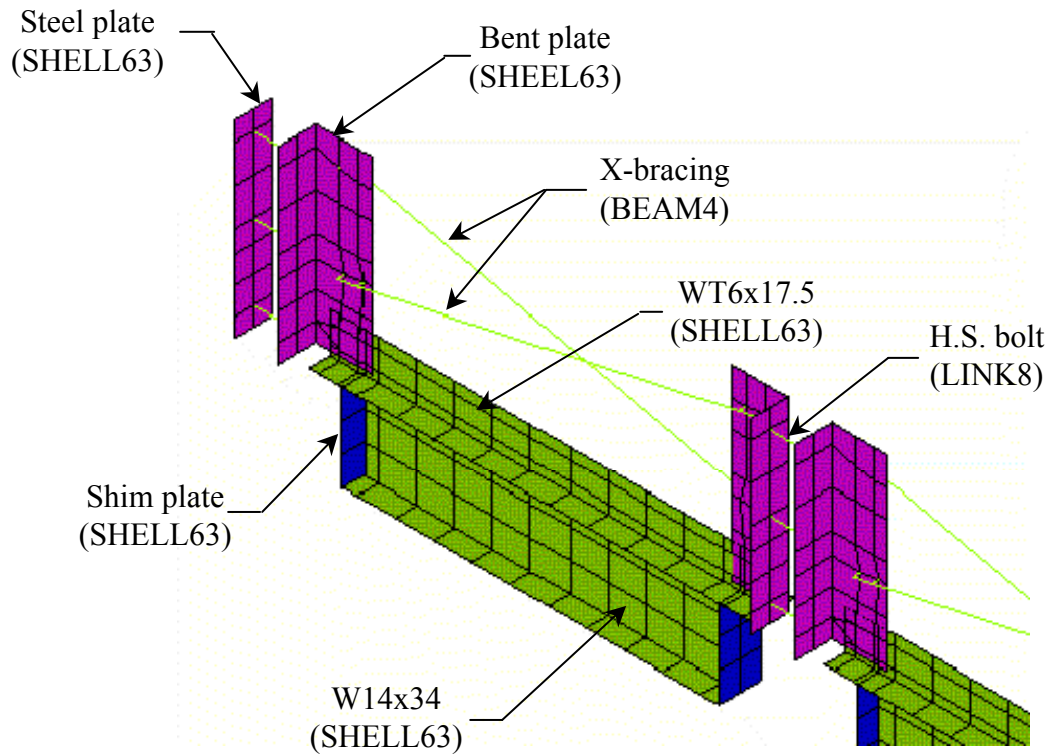


(a) Isometric View

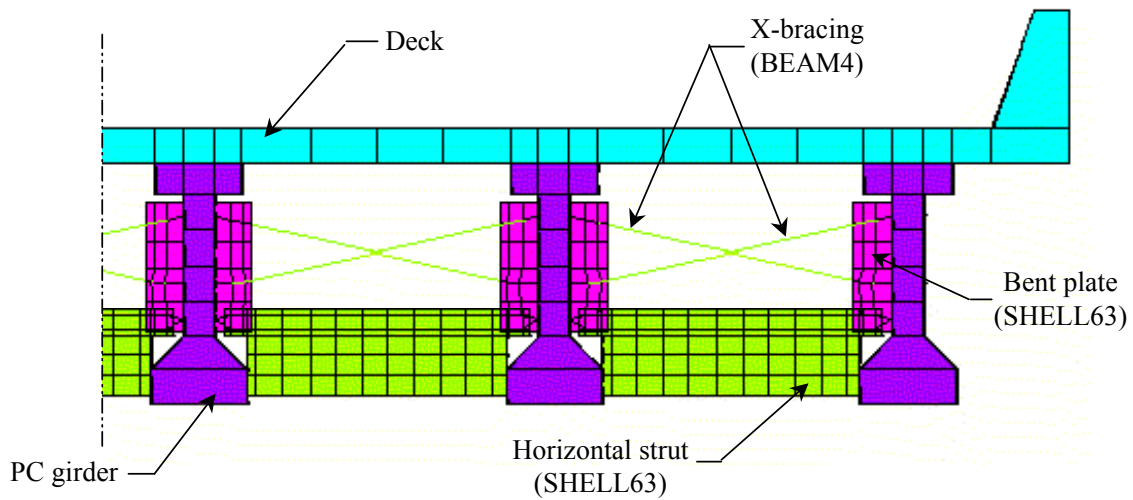


(b) Elevation View

FIGURE 2. Finite-Element Model of the Reinforced Concrete Intermediate Diaphragm

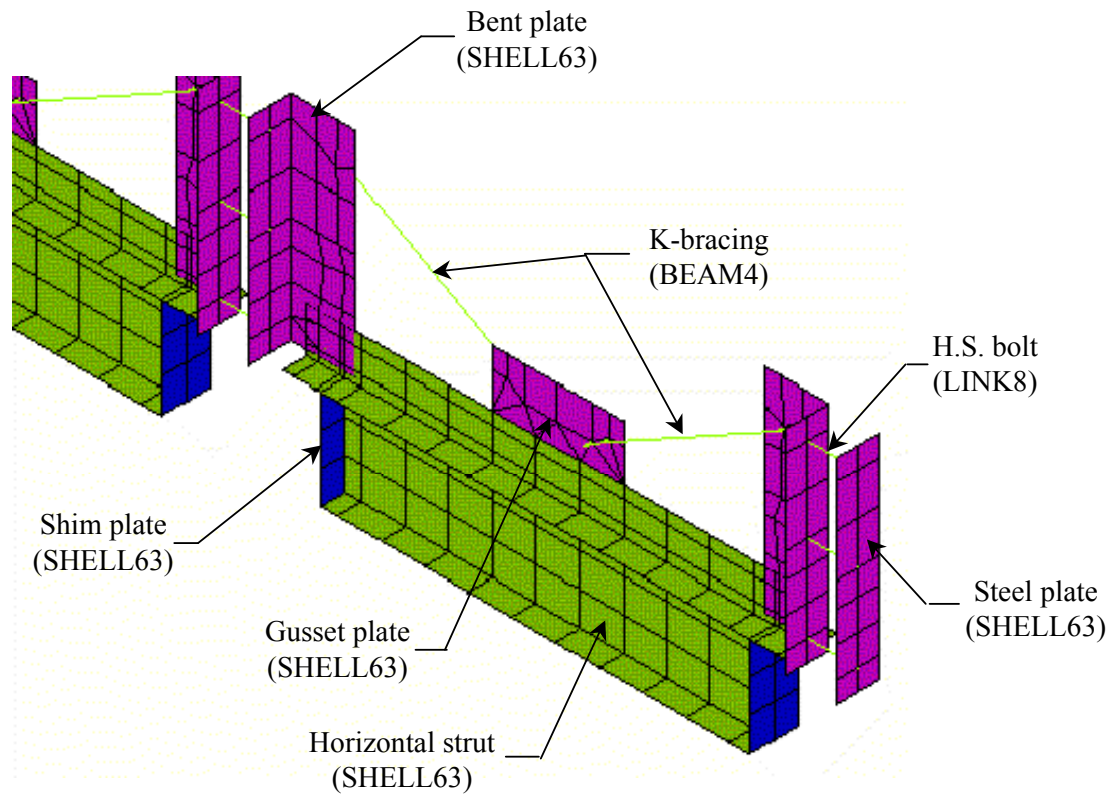


(a) Isometric View

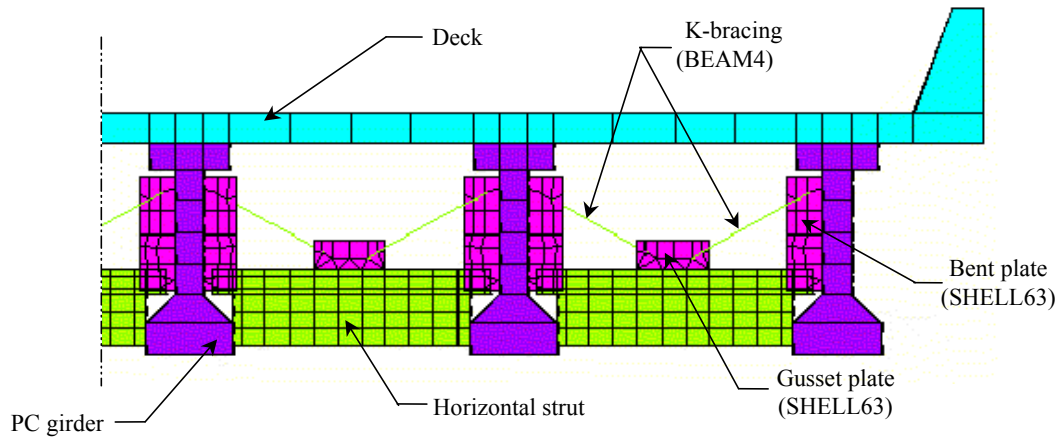


(b) Elevation View

FIGURE 3. Finite-Element Model of the Steel X-Braced Intermediate Diaphragm



(a) Isometric View



(b) Elevation View

FIGURE 4. Finite-Element Model of the Steel K-Braced Intermediate Diaphragm

LOADS

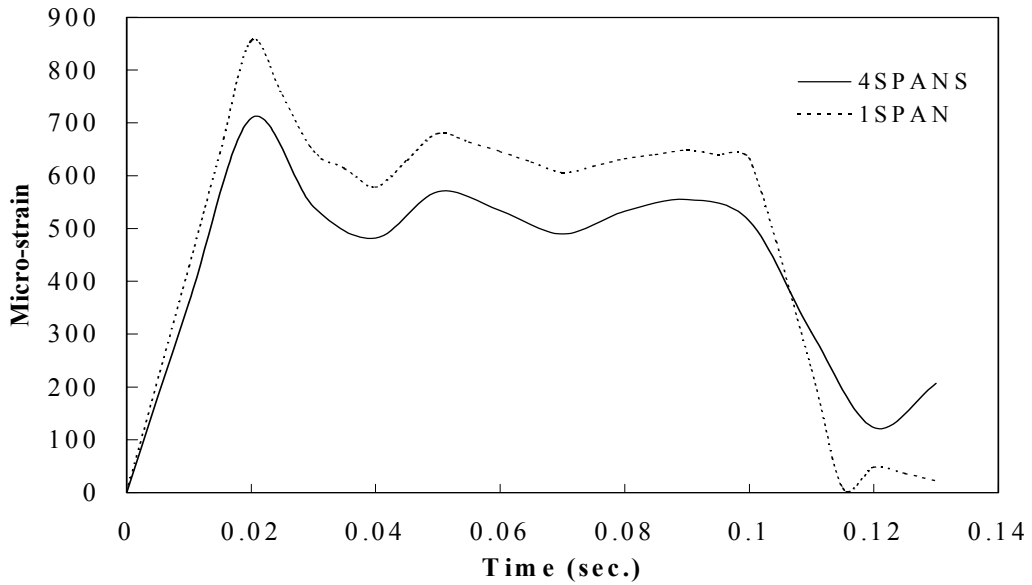
The main factors that are associated with a moving object and influence the magnitude of an impact load that is generated by the object as it impacts a surface are the object's mass, speed, geometrical configuration, and hardness. A search of the published literature that addressed vehicle or object impacts did not reveal any information regarding over-height-vehicle loads striking bridges. Since the main objective of this research was to conduct a comparative study that evaluates the effectiveness of different types of intermediate diaphragms in minimizing structural damage to a bridge superstructure, a precise forcing function did not need to be defined.

One scenario that may occur when an over-height-vehicle load strikes a bridge is as follows: First, the over-height object would impact the bottom flange or web of the first exterior girder. Then, because the vehicle would not suddenly stop, the object being transported could displace downward, as the vehicle-suspension system reacts to the impact, which would allow the object to pass beneath the girder. As the vehicle-suspension system rebounds, the object could displace upwards and cause additional impacts with some or all of the other bridge girders at either their bottom flange or somewhere on their web. Multiple-girder impacts were not included in this study because the reduction in the impact-force magnitude resulting from a reduction in the speed of the vehicle after the first impact is unknown. In this research, a single-impact load was applied on either exterior girder for a single direction of travel, since these loading conditions induce the most severe responses for an impacted girder.

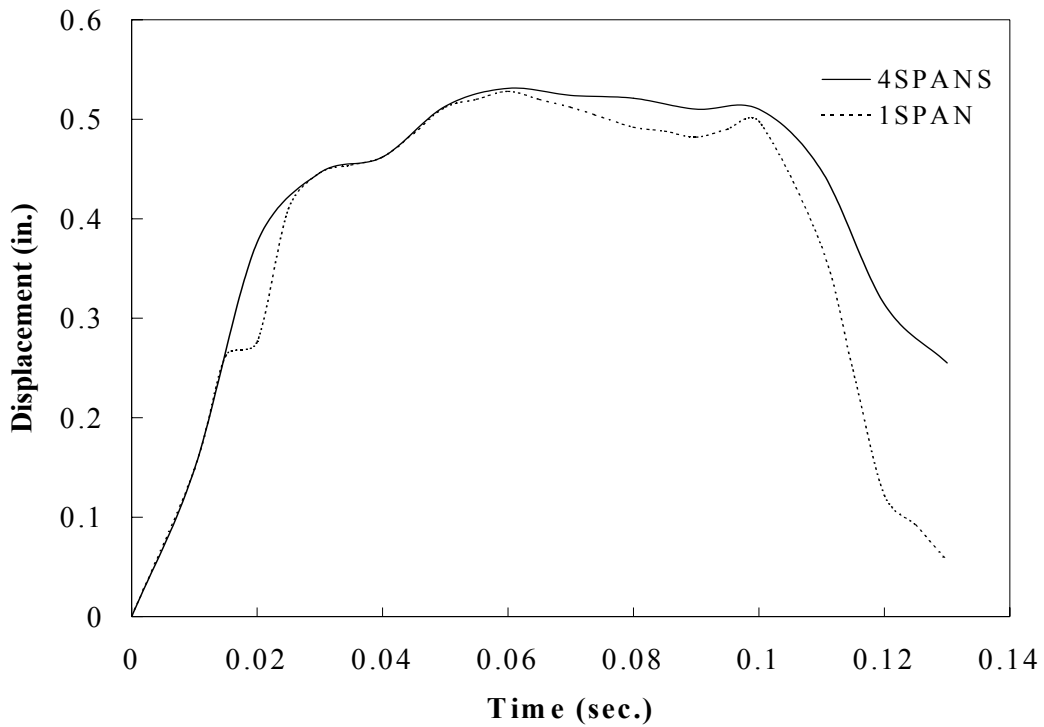
To simulate the impact resulting from an over-height-vehicle load passing beneath the bridge and striking the bottom flange of an exterior bridge girder, an impact load was defined by its duration time and magnitude. Based on published articles that discussed car-crash tests, a 0.10-sec., impact-duration time was selected. A constant-magnitude, impact force was selected to keep the maximum, principle-tensile strains near to or below the modulus-of-rupture strain for the concrete in the PC girders when intermediate diaphragms were incorporated in the analytical models. Two different rectangular, impact pulses were used to represent an impact force that is generated by an over-height-vehicle collision with a PC girder. A maximum load of 120 kips (530 kN) and 60 kips (270 kN) were selected when the impact load was applied directly at and away from, respectively, the midspan of the bridge.

ANALYSES OF ONE SPAN AND COMPLETE BRIDGE MODEL

To simplify the analytical work and to reduce the computational requirements, an investigation was conducted to determine whether a finite-element model for only an interior span of a four-span bridge would predict, with sufficient accuracy, the PC girder strains and displacements that are obtained from an analysis of a four-span, finite-element model. Even though the pier structures were not included in the finite-element models, their lateral stiffness was represented by horizontal springs at the pier locations. These two analytical models did not have any intermediate diaphragms.

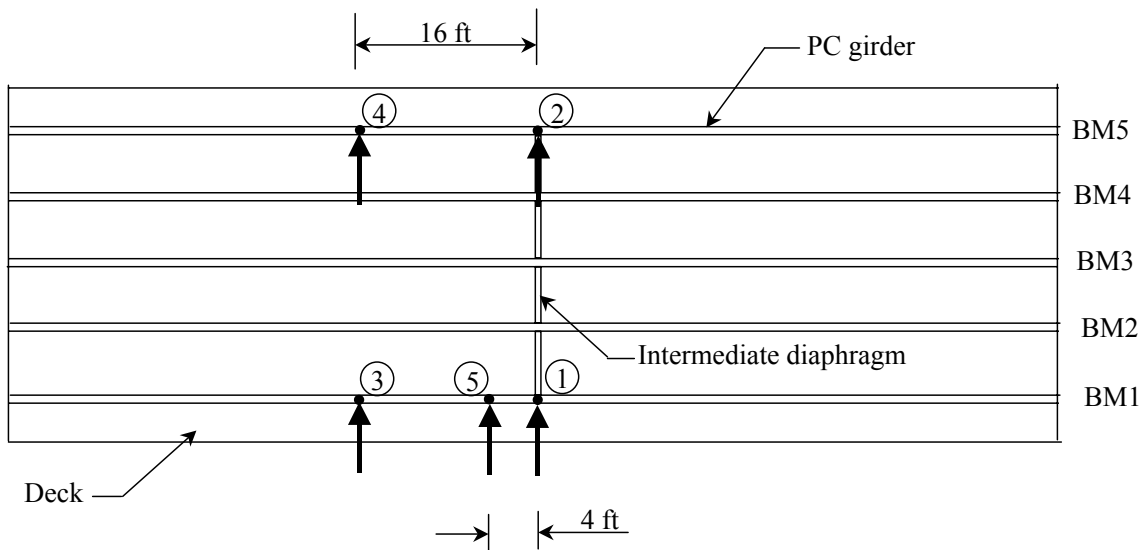


(a) Maximum Principal-Tensile Strains

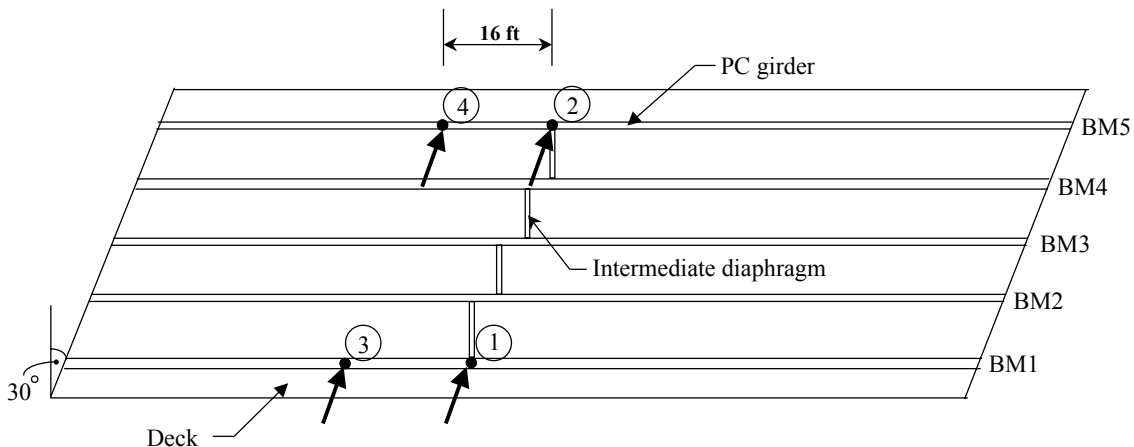


(a) Horizontal Displacements

FIGURE 5. Finite Element Results for the Four-Span and One-Span Models When the Load is Applied at Mid-Span of Girder BM1 (1 in. = 25.4 mm)



(a) Locations of Loading Points for the Non-Skewed Bridge



(b) Location of Loading Points for the Skewed Bridge

FIGURE 6. Loading Points (1 in. = 305 mm)

The maximum, principal-tensile strains in and the corresponding, horizontal displacements for the loaded girder are presented in Figs. 5a and 5b, respectively, of the four-span model and the one-span model. These strains and displacements were induced by a 120-kip (530-kN) lateral-impact load with a 0.10-sec. duration time that was applied at the mid-span of the first exterior girder (girder BM1 shown in Fig. 6a) for traffic that travels under the bridge. These strains occurred in the girder cross section containing the applied load for the top fibers of the girder web. The displacements were at the bottom flange and at the mid-span of the girder. Both the strain and displacement responses were the largest of those load effects for the loaded girder that were

predicted by the finite-element models. The figure shows very similar strain and displacement behaviors for the two analytical models. Only about a 15% difference occurred in the magnitudes of the maximum, principal-tensile strains. The displacement responses predicted by the two, finite-element models were essentially identical for the 0.10-sec. period for the applied impact load. The differences in the girder responses that were predicted by the two, finite-element models and shown in Fig. 5 were not significant enough to affect the objectives of the research. Therefore, the single-span, finite-element model was selected to adequately represent the girder responses to lateral-impact forces. A similar, single-span model was developed for the skewed bridge. Andrawes (4) provided additional information regarding the finite-element models for both the non-skewed and skewed bridges.

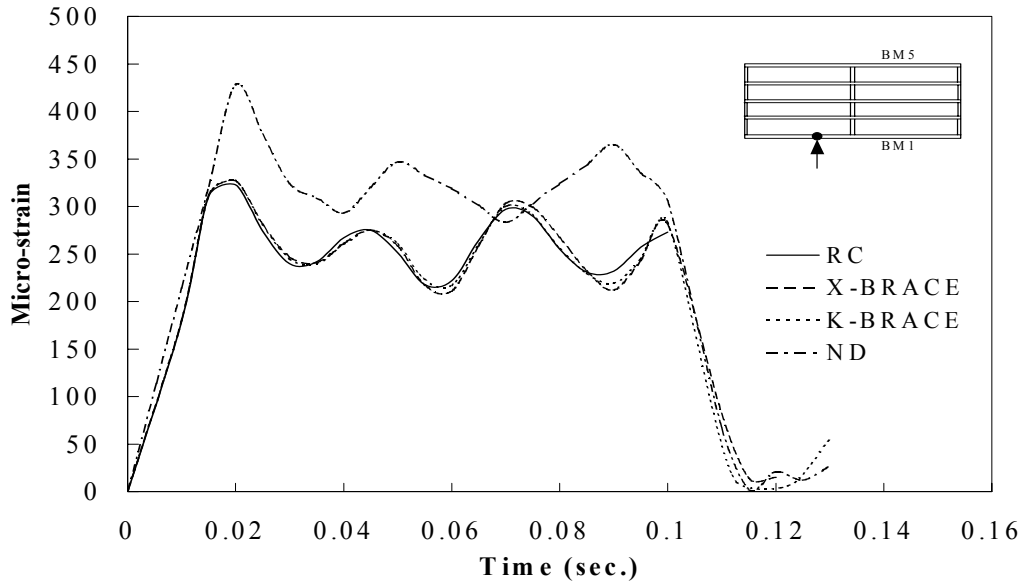
ANALYSIS OF PROTOTYPE BRIDGES

For the non-skewed bridge, the horizontal, impact load was applied to the bottom flange of an exterior girder at one of five locations shown in Fig. 6a. Load positions 1 and 2 were at the mid-span of girders BM1 and BM5, respectively. These locations matched the location for the intermediate diaphragms. Load positions 3 and 4 were applied at 16 ft (4880 mm) to the left of the intermediate diaphragm and on girders BM1 and BM5, respectively. As the analytical study progressed, the researchers decided to apply an impact load at load position 5 that was at 4 ft (1220 mm) to the left of the intermediate diaphragm location. This fifth, load location was considered to account for an impact load that was applied close to but not at the intermediate diaphragm location. Figure 6b shows four, impact-load locations for a skewed bridge. An impact load was not placed at load-position 5 for the skewed bridge.

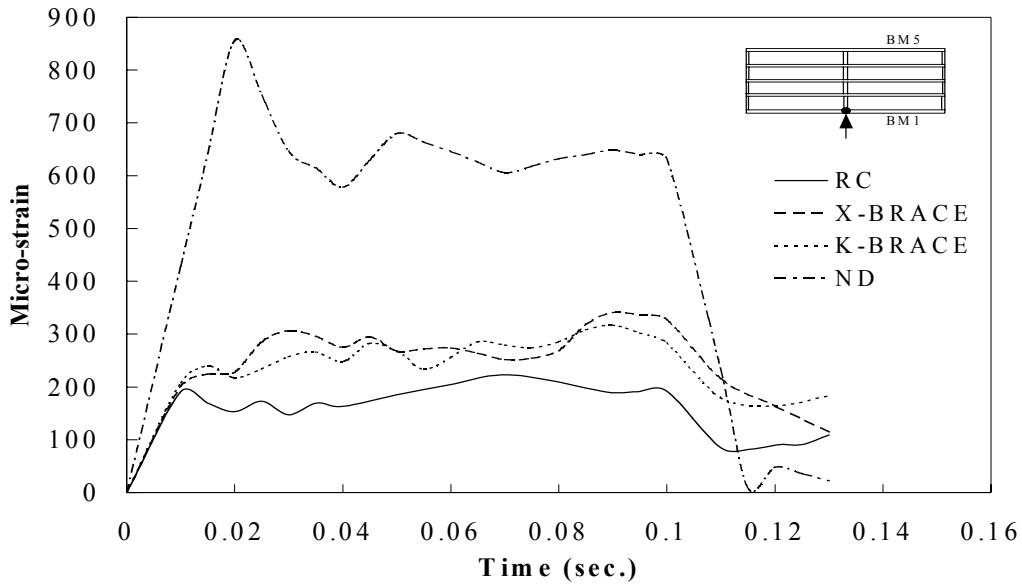
When the impact load occurred at the location of an intermediate diaphragm, as shown in Fig. 7a, the decrease in the maximum, principle-tensile strains from those strains for the bridge without intermediate diaphragms (ND curve) was significant and dependent on the type of intermediate diaphragm. When the impacted load occurred at 16 ft (4880 mm) from the midspan of girder BM1, as shown in Fig. 7b, those strains were about 25% less than the corresponding strains for the bridge without intermediate diaphragms and basically independent on the type of intermediate diaphragm.

Figures 8a and 8b show the magnitude of the maximum, principal-tensile strains in the impacted girder (girder BM1) and the first interior girder (girder BM2), when the impact load is applied at the intermediate diaphragm location for a non-skewed bridge and a skewed bridge, respectively. For both bridge alignments, the RC intermediate diaphragms provided the largest degree of impact protection to the impacted girder, as indicated by the heights of the strain bars shown in these graphs. The steel, X-brace and K-brace, intermediate diaphragms provided essentially the same amount of impact protection to the impacted girder, as indicated by the essentially, equivalent-strain magnitudes. The presence of the RC intermediate diaphragms reduced the magnitude of the maximum, principal-tensile strain to about 28% and 35% of that strain for the no intermediate diaphragm condition for the non-skewed and skewed bridges, respectively. The use of either the steel, X-braced or K-braced, intermediate diaphragms reduced the maximum, principal-tensile strain in girder BM1 to about 40% and 60% of that strain for the no intermediate diaphragm condition for the non-skewed and skewed bridges, respectively. Figure 8a shows that the magnitude of the maximum, principal-tensile strains, which are induced in the first interior girder (girder BM2) for the non-skewed bridge, are smaller for the bridge with RC intermediate diaphragms than for the bridge with either steel, X-braced or K-braced, intermediate diaphragms. However, for the skewed bridge, Fig. 8b shows that the use of either configuration for the steel intermediate diaphragms will induce less strain in girder BM2 than that for the same bridge with

RC intermediate diaphragms. This difference in the behavior between the skewed and non-skewed bridges was attributed to the staggered alignment of the intermediate diaphragms for a skewed bridge. When intermediate diaphragms are in alignment for a non-skewed bridge, a larger amount of the impact force, which is induced in the first intermediate diaphragm, is transferred to the rest of the diaphragms than that for the skewed bridge where the intermediate diaphragms are not in alignment.

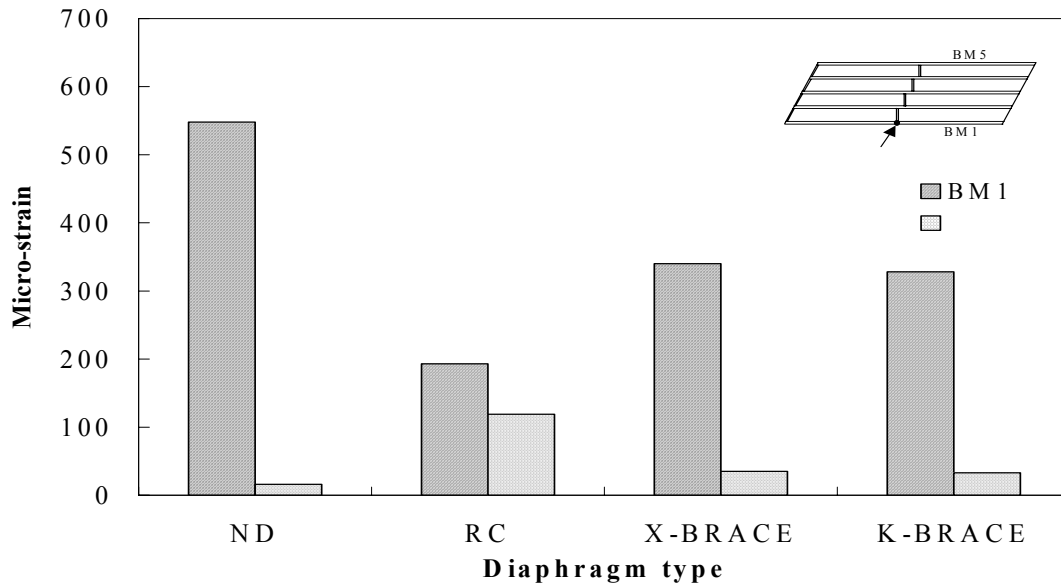


(a) Load at the Mid-Span

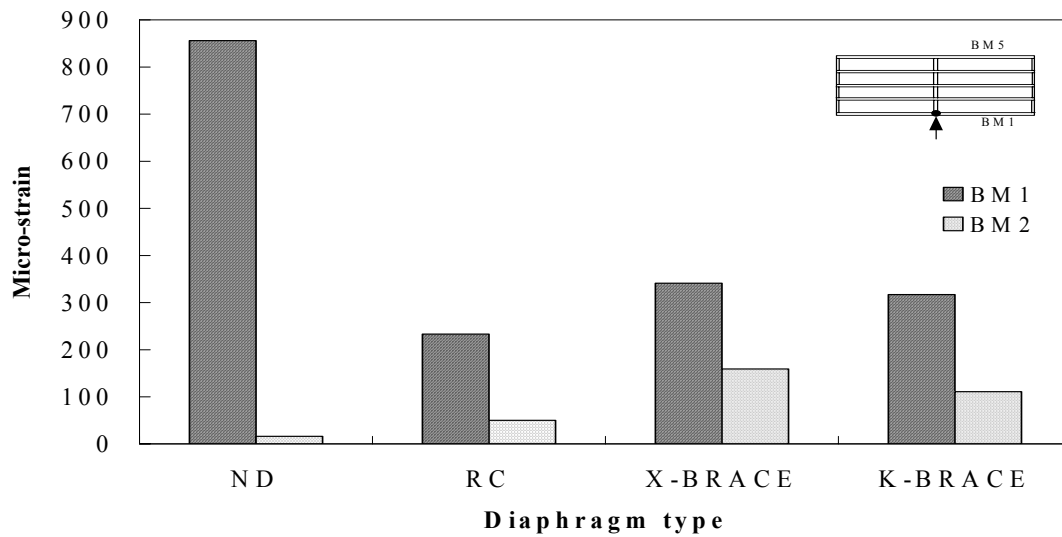


(b) Load at 16 ft (4880 mm) from the Mid-Span

FIGURE 7. Maximum Principal Tensile-Strain in Girder BM1 for the Non-Skewed Bridge



(a) Non-Skewed Bridge



(b) Skewed Bridge

FIGURE 8. Maximum Principal-Tensile Strains in Girders BM1 and BM2

CONCLUSIONS

The results summarized in this manuscript illustrated that when a lateral-impact load was applied directly at the diaphragm locations in a bridge structure, the RC intermediate diaphragm provides the bridge girders with a higher degree of impact protection than that provided by either of the two types of steel intermediate diaphragms that were presented in this study. However, when an over-height-vehicle load strikes a bridge girder away from a diaphragm location, the degree of impact protection provided by each of the three types of intermediate diaphragms was almost the same.

ACKNOWLEDGEMENTS

The research presented in this paper was conducted by Iowa State University, administered by the Center for Transportation Research and Education, and sponsored by the Iowa Department of Transportation, Highway Division, through the Highway Research Board.

REFERENCES

1. Shanafelt G.O., and W.B. Horn. *Damage evaluation and repair methods for prestressed concrete bridge members*. NCHRP Report 226, 1980.
2. De Salvo G.J., and J.A. Swanson. *ANSYS Engineering Analysis System User's Manual*. Volumes 1-4. Houston. Penn., USA, 1985.
3. Abendroth, R.E., F.W. Klaiber, and M.W. Shafer. *Lateral load resistance of diaphragms in prestressed concrete girder bridges*. Iowa Department of Transportation, Project HR-319, ISU-ERI-Ames-92076, 1991.
4. Andrawes, B.O. Lateral impact response for prestressed concrete girder bridges with intermediate diaphragms. *Thesis*, Iowa State University, 2001.